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# SHORT-TERM HOT HARDNESS CHARACTERISTICS OF ROLLING-ELEMENT STEELS

*by James L. Chevalier, Marshall W. Dietrich,  
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## SUMMARY

Short-term hot hardness studies were performed with five vacuum-melted steels. These were AISI 52100, AISI M-1, AISI M-50, Halmo, and WB-49. Hardness measurements on each material were taken at elevated temperatures in an electric furnace with a low oxygen environment. This ensured that decarburization and oxidation would not affect the results. Test temperatures ranged from 294 to 887 K (70° to 1140° F).

Based upon the criterion of a minimum Rockwell C hardness of 58 for rolling-element systems, the limiting temperatures of all the materials studied were dependent on initial room temperature hardness and tempering temperature. For the same initial room temperature hardness, the short-term hot hardness of AISI M-1, AISI M-50, Halmo, and WB-49 are identical from 294 to 812 K (70° to 1000° F) and independent of material composition.

The short-term Rockwell C hardness at temperature for the materials studied can be determined within  $\pm 1$  point Rockwell C (Rc) hardness from the following equation:

$$(Rc)_T = (Rc)_{RT} - \alpha \Delta T^\beta$$

where

$(Rc)_T$       Rockwell C hardness at operating temperature

$(Rc)_{RT}$      Rockwell C hardness at room temperature

$\Delta T$         change in temperature,  $T_T - T_{RT}$

$T_T$         operating temperature, K; °F

$T_{RT}$        room temperature, K; °F

$\alpha$         temperature proportionality factor,  $(K)^{-\beta}$ ;  $(°F)^{-\beta}$

$\beta$         exponent

This equation is valid for AISI 52100 from 294 K to 533 K (70° to 500° F), and for the high-speed tool steels from 294 K to 812 K (70° to 1000° F).

## INTRODUCTION

AISI 52100 has been the most commonly used rolling-element bearing material. This material has been limited to applications where the maximum temperatures will not exceed its tempering temperature of 450 K (350<sup>0</sup> F). If it is maintained at the temperature for any length of time, its hardness will drop below Rockwell C 58, which is considered a minimum hardness for rolling-element bearing components. At a hardness below this value, brinelling and plastic deformation can be excessive during normal operation (refs. 1 and 2).

In recent years tool steels have been used with increasing frequency as a rolling-element bearing material for service above 450 K (350<sup>0</sup> F) such as in turbojet engines. In these applications, dimensional stability, retention of hot hardness, wear resistance, and oxidation resistance at elevated temperatures are particularly important. Typical of these high-speed steels are AISI M-1, M-2, M-10, M-50, and Halmo. These alloys contain elements such as molybdenum, tungsten, and vanadium, which are all strong carbide formers. The alloy carbides that form not only provide increased hardness of the material, but also help to retain this hardness at elevated temperatures. These materials are through-hardenable steels. That is, material hardness is attained throughout the part by heat treatment rather than by a case hardening procedure such as carburizing.

These high-speed tool steels are more difficult to grind and finish than AISI 52100 (refs. 1 and 2) because of the greater amount of hard alloy carbides present in them. However, their hot hardness characteristics more than make up for this disadvantage. For example, based on the hot hardness minimum of Rc 58, it has been estimated that AISI M-50 should have an upper temperature limit in excess of 589 K (600<sup>0</sup> F). For this reason, AISI M-50 is being specified for many current turbine engine bearings. Likewise, M-1, M-2, and M-10 may be useful well above the 450 K (350<sup>0</sup> F) limit of AISI 52100.

There have been studies performed to compare the hot hardness properties of various materials (refs. 3 and 4). However, these studies have not compared the hot hardness properties of the same material after tempering to various room temperature hardness levels, nor have different materials tempered to the same room temperature hardness been compared.

The objectives of the research reported herein were (1) to reaffirm the hot hardness properties of AISI 52100, AISI M-1, AISI M-50, Halmo, and WB-49, and (2) to investigate the relative hot hardness properties of these same materials after tempering to various room temperature hardness levels. These objectives were accomplished by testing groups of each material for hardness from room temperature to 889 K (1140<sup>0</sup> F).

Measurements were obtained with a standard hardness tester fitted with a low oxygen environment electric furnace. All specimens for each material were made from a single vacuum-melted ingot, except where noted.

## BACKGROUND

Confusion often arises over metallurgical terms. Therefore, some of these terms are defined here. Annealing is a general term applied to several softening operations including full annealing, normalizing, process annealing, and spheroidizing. In this report, annealing is used in context to refer to spheroidizing.

Spheroidizing is a softening process usually restricted to high-carbon steels. By heating the steel to a temperature below, but very near the  $A_1$  (eutectoid) temperature for a long period, a structure having relatively large particles of iron carbide in a matrix of ferrite is produced. This structure is the softest and most ductile one possible in the high-carbon and tool steels. For high-speed steels, the annealing temperature is approximately 1140 K (1600<sup>o</sup> F) (ref. 5).

In tempering, the strong, brittle martensitic structure obtained by quenching is given some ductility. In some high-carbon materials, hardness and strength must be sacrificed to obtain the desired ductility and toughness (ref. 5). However, in high-speed tool steels, a precipitation hardening reaction occurs at tempering temperatures from 811 K to 867 K (1000<sup>o</sup> to 1100<sup>o</sup> F) which results in a material with the desired toughness, and approximately the same hardness as the as-quenched material (ref. 6). For high-speed tool steels, this is referred to as secondary hardening.

## TEST SPECIMENS

The materials used in this investigation were consumable vacuum-melted (CVM) AISI 52100, AISI M-1, AISI M-50, Halmo, and WB-49. The chemical compositions of these materials are presented in table I. Photomicrographs of the individual materials are shown in figure 1. All the high-speed steels and WB-49 show typically larger carbides than AISI 52100.

All specimens for each material with the exception of AISI M-50 were made from one vacuum-melted ingot. Two different vacuum-melted ingots of M-50 material were used. The specimens were heat treated according to the heat treat schedules contained in table II. Room temperature hardness, retained austenite, and grain size are also presented in this table. ASTM cleanliness ratings are given in table III.

## APPARATUS AND PROCEDURE

Samples were prepared for hardness testing by sectioning with a cutoff wheel and then grinding flats with a belt grinder. Both sectioning and grinding were done by hand with a copious supply of coolant to prevent overheating of the test specimens. The hardness of the material was measured at both room and elevated temperature using a standard hardness tester fitted with a low oxygen environment electric-resistance-type furnace (fig. 2). The low oxygen environment was used to eliminate any possible effect of surface oxidation and decarburization on the hardness measurements. Hardness tests were performed using a 150-kilogram load and a Rockwell C diamond indenter.

Hardness measurements were taken immediately after reaching an equilibrium temperature and before the heat input was increased for the next higher temperature. A minimum of two hardness measurements were taken for each temperature and material. Approximately 1/2 hour elapsed before equilibrium was reached at each test temperature. Another 1/2 hour elapsed while measurements were being taken.

## RESULTS AND DISCUSSION

Hot hardness measurements were made for groups of specimens of AISI 52100, AISI M-1, AISI M-50, Halmo, and WB-49. Each material with the exception of AISI M-50 was from one vacuum-melted ingot with individual specimens varying with respect to room temperature hardness. The results of these measurements are shown in figure 3.

AISI 52100 has been considered useful to temperatures of about 450 K (350° F). This was based on the commonly accepted criterion that, for bearing components, the minimum hardness at operating temperature is Rc 58 (ref. 1). While the data of figure 3(a) might suggest that AISI 52100 could be used at temperatures higher than 450 K (350° F), long time exposure to temperatures greater than the tempering temperature of 450 K (350° F) would result in a substantial reduction in hardness.

The data for all the steels of figure 3 suggest that regardless of the initial hardness, the hot hardness of the individual materials show the same functional dependence. To verify this observation, the change in hardness  $\Delta R_c$  (hardness at room temperature minus hardness at test temperature) was plotted against temperature in figure 4. This had the effect of normalizing all the samples of each material to the same room temperature hardness. These data show that the changes in hardness with increasing temperature of AISI 52100, AISI M-1, AISI M-50, Halmo, and WB-49 are all independent of initial hardness.

The normalized data from figure 4 for AISI M-1, AISI M-50, Halmo, and WB-49 are combined in figure 5. These plots illustrate that the change in hardness of these mate-

rials is also independent of material composition. Therefore, the only limiting variables in using these materials are their tempering temperatures, their ability to maintain a Rockwell C hardness in excess of 58 at operating temperature and their initial room temperature hardness. These data suggest that there are no differences in the hot hardness characteristics of AISI M-1, AISI M-50, Halmo, and WB-49.

The data of figure 5(a) when plotted on log-log coordinates in figure 5(b), can be represented by a straight line having the form

$$(Rc)_T = (Rc)_{RT} - \alpha \Delta T^\beta$$

where

$(Rc)_T$	Rockwell C hardness at operating temperature
$(Rc)_{RT}$	Rockwell C hardness at room temperature
$\Delta T$	change in temperature, $T_T - T_{RT}$
$T_T$	operating temperature, K; $^{\circ}\text{F}$
$T_{RT}$	room temperature, K; $^{\circ}\text{F}$
$\alpha$	temperature proportionality factor, $(\text{K})^{-\beta}$ ; $(^{\circ}\text{F})^{-\beta}$
$\beta$	exponent

For AISI 52100 (fig. 5(b)) between 294 K and 533 K ( $70^{\circ}$  and  $500^{\circ}$  F)

$$(Rc)_T = (Rc)_{RT} - 9.2 \times 10^{-4} \Delta T^{1.6}$$

where  $\Delta T$  is in degrees Kelvin. If  $\Delta T$  is given in degrees Fahrenheit, then

$$(Rc)_T = (Rc)_{RT} - 3.4 \times 10^{-4} \Delta T^{1.6}$$

For the other materials studied (fig. 5(b)), between 294 K and 812 K ( $70^{\circ}$  and  $1000^{\circ}$  F),

$$(Rc)_T = (Rc)_{RT} - 1.3 \times 10^{-3} \Delta T^{1.4}$$

where  $\Delta T$  is in degrees Kelvin. When  $\Delta T$  is given in degrees Fahrenheit,

$$(Rc)_T = (Rc)_{RT} - 5.4 \times 10^{-4} \Delta T^{1.4}$$

To illustrate the broad applicability of the hardness equations, short-term hardness data from reference 7 and a private communication from A. M. Bayer (Teledyne Vasco, Latrobe, Pa.) are plotted in figure 6 and compared to hardness predictions from the aforesaid equations shown above. The data from reference 7 for AISI 52100 are shown in figure 6(a) and for AISI M-2, M-10, M-42, and T-1, in figure 6(b). The data from A. M. Bayer (Teledyne Vasco, Latrobe, Pa.) for AISI 52100 are shown in figure 6(a) and for AISI M-1, M-2, M-42, M-50, T-1, and WB-49, in figure 6(c). The data from A. M. Bayer (Teledyne Vasco, Latrobe, Pa.) have somewhat more scatter than those of reference 7 and of this report. However, all sets of data generally follow the predicted values.

The general nature of the equation can be understood from the tempering characteristics of high-speed steels and AISI 52100. These materials are precipitation hardening alloys (ref. 6). As the temperature of the material is raised, it begins to overage and soften. When the operating temperature nears the tempering temperature, this process is accelerated and the hardness decreases more rapidly. As the test temperature is raised beyond the tempering temperature, the precipitation hardening precipitate particles increase in size and decrease in number and the material begins to spheroidize (refs. 6 and 8). At this point, the greatest decrease in hardness occurs and the hardness of the material tends to decrease toward the fully annealed condition.

The difference in hot hardness capability between the AISI 52100 and the high-speed steels can be explained by the difference in the precipitation hardening phase. In AISI 52100, the precipitate is an iron carbide ( $\text{Fe}_{2.4}\text{C}$ ) called epsilon carbide, whereas in the high-speed steels the precipitates are  $\text{W}_2\text{C}$  and/or  $\text{Mo}_2\text{C}$  (ref. 6). Thus, it would be expected that all materials which obtain their hot hardness from the precipitation of  $\text{W}_2\text{C}$  or  $\text{Mo}_2\text{C}$  would have similar hot hardness characteristics as the high-speed steels show to 812 K (1000° F). Similarly, those materials which obtain their hot hardness from the precipitation of epsilon carbide would be expected to have the same hot hardness characteristics as AISI 52100 up to 450 K (350° F).

In this study, the materials tested were exposed to elevated temperatures only long enough (30 min) to make hardness measurements after having reached a predetermined equilibrium temperature (approximately 30 min). The effects of exposure to elevated temperatures for longer periods of time were not studied as a part of the research reported herein. However, time at temperature is just as important a factor as temperature itself with regard to hot-hardness characteristics. In fact, in heat treating practice, these two factors are considered interchangeable. That is, if the heat treating temperature is reduced, an identical structure can be obtained by increasing the exposure time at the lower temperature.



## SUMMARY OF RESULTS

Short-term hot hardness studies were performed with five vacuum-melted steels. These were AISI 52100, AISI M-1, AISI M-50, Halmco, and WB-49. Hardness levels of each material were measured at elevated temperatures in an electric furnace with a low oxygen environment. Test temperatures ranged from 294 to 887 K (70<sup>0</sup> to 1140<sup>0</sup> F). The following results were obtained:

1. Based upon the criterion of a minimum Rockwell C hardness of 58 for rolling-element systems, the limiting temperatures of all the materials studied were dependent on initial room temperature hardness and tempering temperature.

2. For the same initial room temperature hardness, the short-term hardness at temperature of AISI M-1, AISI M-50, Halmco, and WB-49 are identical from 294 K to 812 K (70<sup>0</sup> to 1000<sup>0</sup> F) and independent of material composition.

3. The short-term Rockwell C hardness at temperature for the materials studied can be predicted within  $\pm 1$  point Rockwell C (Rc) hardness by the following equation:

$$(Rc)_T = (Rc)_{RT} - \alpha \Delta T^\beta$$

where

$(Rc)_T$       Rockwell C hardness at operating temperature

$(Rc)_{RT}$      Rockwell C hardness at room temperature

$\Delta T$         change in temperature,  $T_T - T_{RT}$

$T_T$         operating temperature, K; <sup>0</sup>F

$T_{RT}$        room temperature, K; <sup>0</sup>F

$\alpha$         temperature proportionality factor,  $(K)^{-\beta}$ ;  $(^0F)^{-\beta}$

$\beta$         exponent

This equation is valid for AISI 52100 between 294 and 533 K (70<sup>0</sup> and 500<sup>0</sup> F) and for the high-speed steels between 294 and 812 K (70<sup>0</sup> and 1000<sup>0</sup> F).

Lewis Research Center,

National Aeronautics and Space Administration,

and

U.S. Army Air Mobility R&D Laboratory,

Cleveland, Ohio, October 26, 1971,

132-15.

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TABLE I. - CHEMICAL COMPOSITION OF BEARING STEELS

Material	Alloying element, percent by weight (balance Fe)										
	C	Si	Mn	S	P	W	Cr	V	Mo	Co	Ni
AISI 52100 <sup>a</sup>	0.96	0.22	0.36	0.012	0.007	---	1.36	---	---	---	----
AISI M-1 <sup>a</sup>	0.81	0.32	0.25	0.007	0.004	1.53	3.76	1.15	8.54	---	0.07
AISI M-2 <sup>b</sup>	0.78 to 0.88	0.2 to 0.4	0.2 to 0.4	-----	-----	5.5 to 6.75	3.75 to 4.5	1.6 to 2.2	4.5 to 5.5	---	----
AISI M-10 <sup>b</sup>	0.89 to 0.90	0.2 to 0.4	0.2 to 0.4	-----	-----	---	3.75 to 4.5	1.8 to 2.2	7.7 to 9.0	---	----
AISI M-42 <sup>b</sup>	1.05 to 1.1	0.15 to 0.30	0.15 to 0.30	-----	-----	1.3 to 1.7	3.5 to 4.0	1.05 to 1.25	9.25 to 9.75	7.75 to 8.25	----
AISI M-50 <sup>a</sup>	0.81	0.14	0.25	0.007	0.004	0.01	3.97	1.07	4.29	---	0.05
AISI T-1 <sup>b</sup>	0.65 to 0.75	0.2 to 0.4	0.2 to 0.4	-----	-----	17.25 to 18.25	3.75 to 4.5	0.9 to 1.3	<sup>c</sup> 1.0	---	----
Halmo <sup>a</sup>	0.59	1.10	0.31	0.007	0.005	---	4.79	0.51	5.22	---	----
WB-49 <sup>a</sup>	1.07	0.02	0.30	0.007	0.006	6.8	4.4	2.0	3.9	5.2	0.04

<sup>a</sup>Actual composition for material studied in this investigation.<sup>b</sup>Nominal composition for this material.<sup>c</sup>Maximum.

TABLE II. - TEST MATERIAL PROPERTIES AND HEAT TREATMENT

(a) SI units

Material	Room temperature hardness, Rockwell C	Retained austenite, percent by volume <sup>a</sup>	Austenitic grain size, ASTM	Heat treatment, K						
				Preheat	Austenitize	Quench	First temper	Subzero cooling	Second temper	Third temper
AISI 52100	59.7 62.3 63.4 64.6 65.1	<2 12.8 15.6 18.4 11.8	12 ↓		(30 min) 1116 to 1144	Oil: 325	(60 min) 394 ↓		(60 min) 505 450 433 394 None	
AISI M-1	62 62.4 64	2.8 3.2 7.2	8- ↓	Salt: 1061, 3½ min	1478	Oil: 322	(120 min) 867 837 812		(120 min) 867 837 812	
AISI M-50 (Group A)	58.9 59.2 61.8	1.8 2.2 ----	8- ↓	Salt: 1061, 3½ min	1398	Oil: 322	(120 min) 867 837 812		(120 min) 867 837 812	(40 min) None None 825
AISI M-50 (Group B)	60 62.4 62.5 63 63.4	---- ---- ---- ---- ----	9.9 ↓	Salt: 1061, 3½ min	1398	Salt: 812 Air: 339	(120 min) b ↓ 797	(90 to 120 min) 194 to 172	(120 min) b ↓ 797	(120 min) b ↓ 797
Halmo	56.3 60.1 62.4	2.6 3.6 4.4	6 to 7 ↓	Salt: 1061, 3½ min	1422	Oil: 322	(120 min) 867 837 812		(120 min) 867 837 812	
WB-49	54.3 58.1 62.7 67.6	<1 <1 <1 5.0	8+ ↓	Salt: 1089, 6 min	Salt: 1492, 6 min	Salt: 936, 6 min	(120 min) 825 ↓		(120 min) 825 ↓	(40 min) 825 923 894 None

<sup>a</sup>Obtained by X-ray diffraction.<sup>b</sup>Tempered between 797 and 837 K. Exact heat treatment unknown.

TABLE II. - Concluded. TEST MATERIAL PROPERTIES AND HEAT TREATMENT

(b) U.S. Customary units

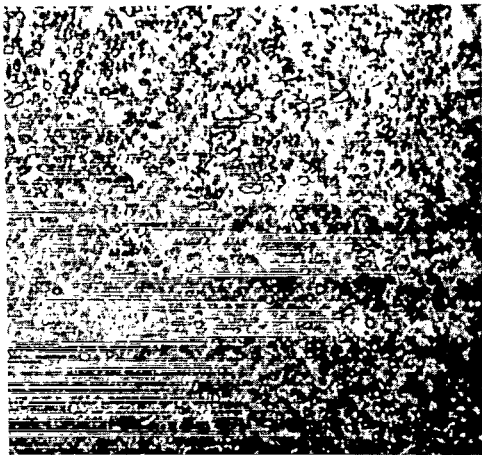
Material	Room temperature hardness, Rockwell C	Retained austenite, percent by volume <sup>a</sup>	Austenitic grain size, ASTM	Heat treatment, °F						
				Preheat	Austenitize	Quench	First temper	Subzero cooling	Second temper	Third temper
AISI 52100	59.7	<2	12		(30 min) 1500 to 1600	Oil: 125	(60 min) 250		(60 min) 450	
	62.3	12.8	↓						350	
	63.4	15.6							320	
	64.6	18.4							250	
	65.1	11.8	↓						None	
AISI M-1	62	2.8	8-	Salt: 1450, 3½ min	2200	Oil: 120	(120 min) 1100		(120 min) 1100	
	62.4	3.2	↓				1050		1050	
	64	7.2	↓				1000		1000	
AISI M-50 (Group A)	58.9	1.8	8-	Salt: 1450, 3½ min	2050	Oil: 120	(120 min) 1100		(120 min) 1100	(40 min) None
	59.2	2.2	↓				1050		1050	None
	61.8	----	↓				1000		1000	1025
AISI M-50 (Group B)	60	----	9.9	Salt: 1450, 3½ min	2050	Salt: 1000	(120 min) b	(90 to 120 min) -110 to -150	(120 min) b	(120 min) b
	62.4	----	↓			Air: 150	↓		↓	↓
	62.5	----								
	63	----	↓				975		975	975
Halmo	56.3	2.6	6 to 7	Salt: 1450, 3½ min	2100	Oil: 120	(120 min) 1100		(120 min) 1100	
	60.1	3.6	↓				1050		1050	
	62.4	4.4	↓				1000		1000	
WB-49	54.3	<1	8+	Salt: 1500, 6 min	Salt: 2225, 6 min	Salt: 1225, 6 min	(120 min) 1025		(120 min) 1025	(40 min) 1025
	58.1	<1	↓							1200
	62.7	<1								1150
	67.6	5.0	↓							None

<sup>a</sup>Tempered between 975° and 1050° F. Exact heat treatment unknown.<sup>b</sup>Obtained by X-ray diffraction.

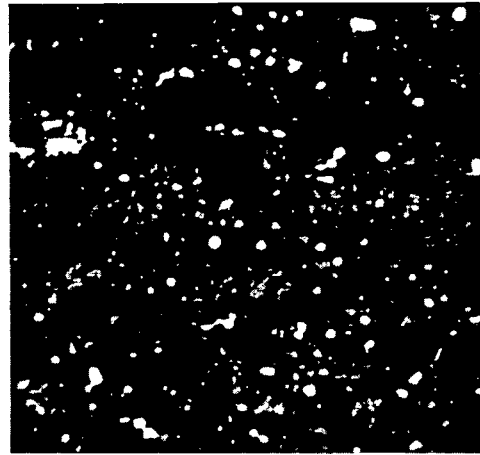
TABLE III. - NONMETALLIC INCLUSION RATINGS OF TEST MATERIALS

[Jernkontoret charts (ASTM specification 45-51).]

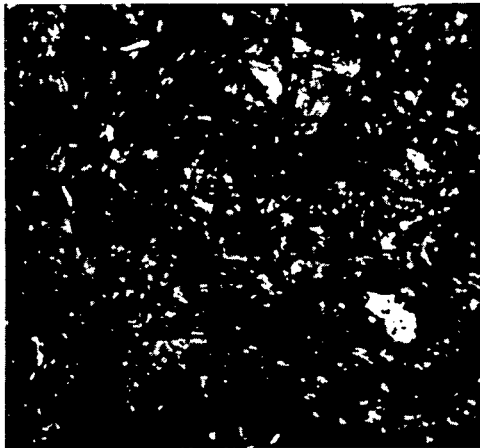
Material	Thin series			Thick series				
	Sulfides	Aluminates	Silicates	Oxides	Sulfides	Aluminates	Silicates	Oxides
AISI 52100	0 to 1	0 to 1	0 to 1	1	0	0 to 1	0 to 1	0 to 1
AISI M-1	0	1.0	0	1.5	0	0	0	0
AISI M-50 (Group A)	0.5	1.5	0.5	2.0	0	0.5	0	0.5
AISI M-50 (Group B)	0	0	0	1.0	0	0	0	0
Halmo	1.5	2.0	0.5	2.0	0	0	0	0.5
WB-49	1.5	0	0	1.0	---	-----	-----	-----



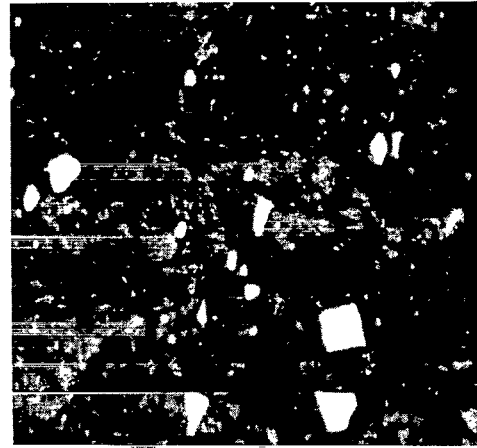
(a) AISI 52100.



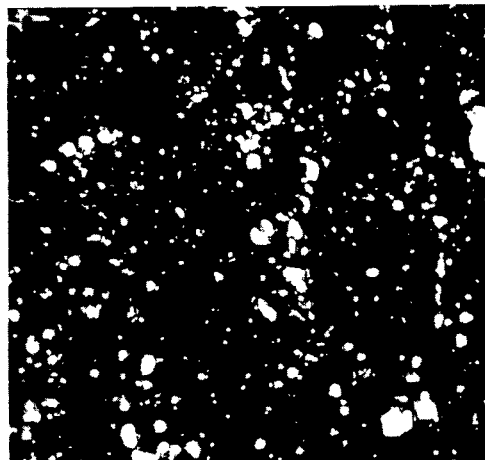
(b) AISI M-1.



(c) AISI M-50 (Groups A and B).



(d) HaImo.



(e) WB-49.

0.00254 cm  
(0.001 in.)

Figure 1. - Photomicrographs of materials. Etchant: 2 percent nital.

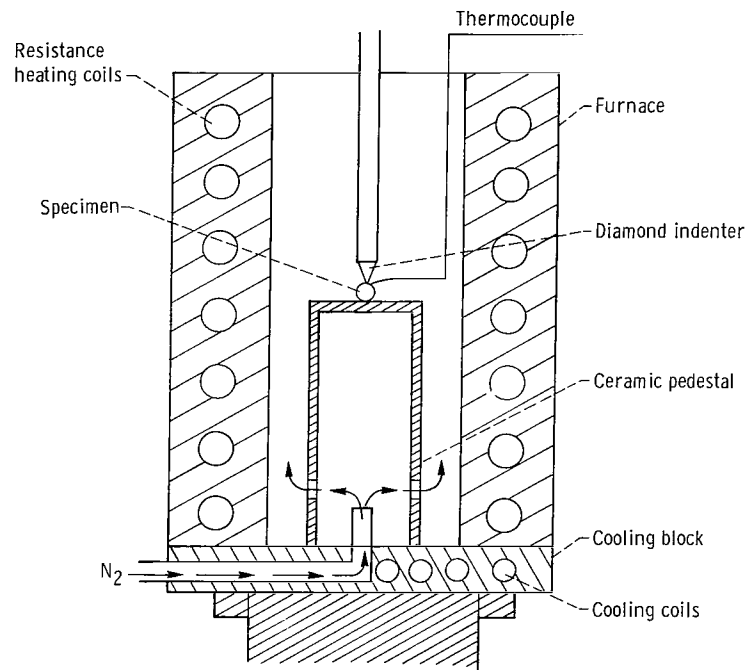


Figure 2. - Cross section of hot hardness tester.



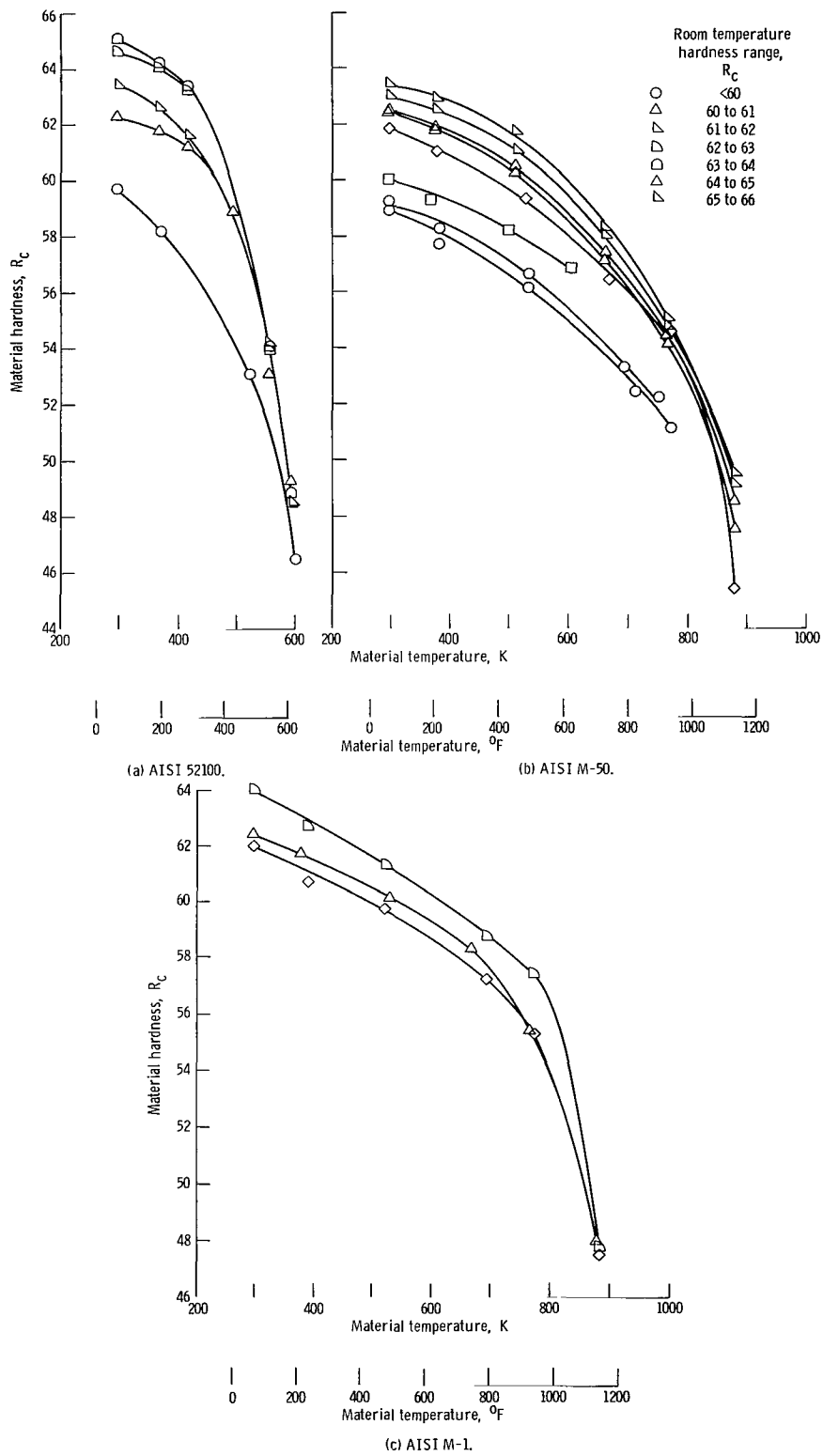
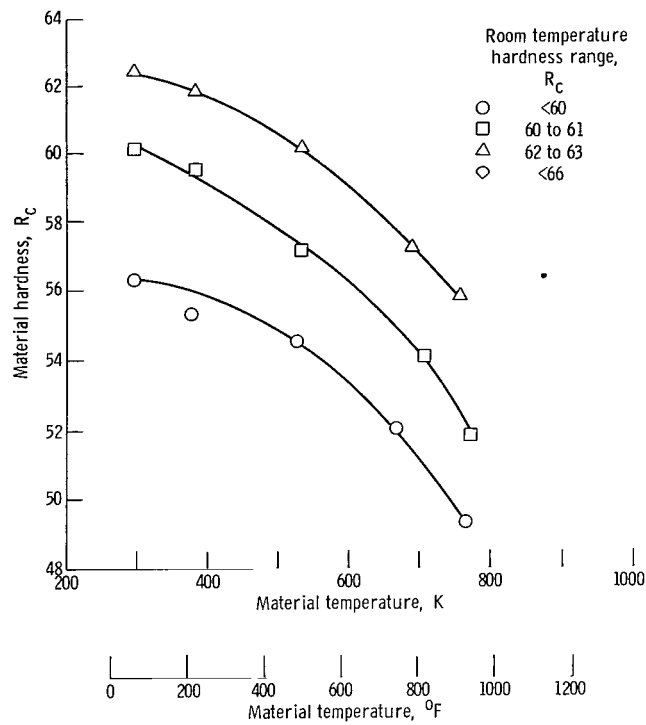
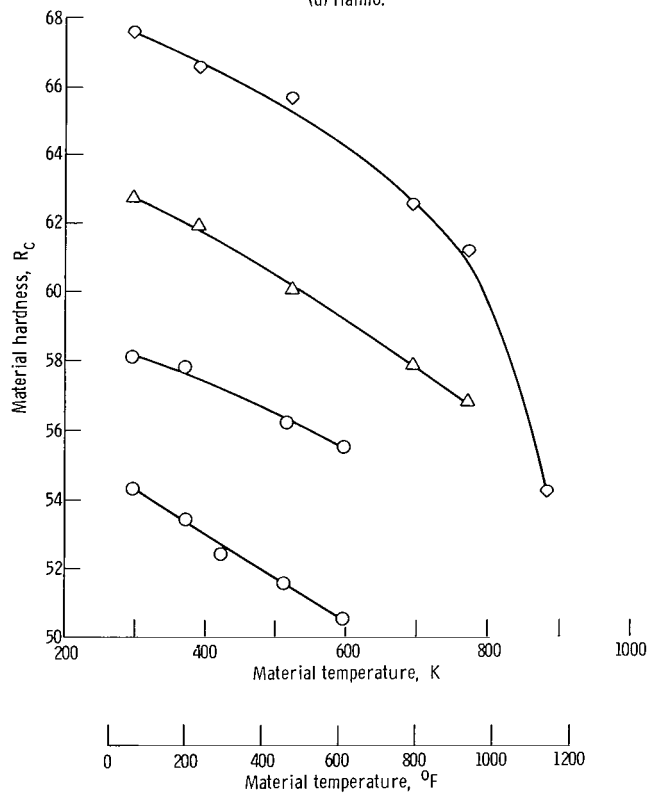


Figure 3. - Effect of temperature on short-term hardness of five bearing materials.



(d) Halmo.



(e) WB-49.

Figure 3. - Concluded.

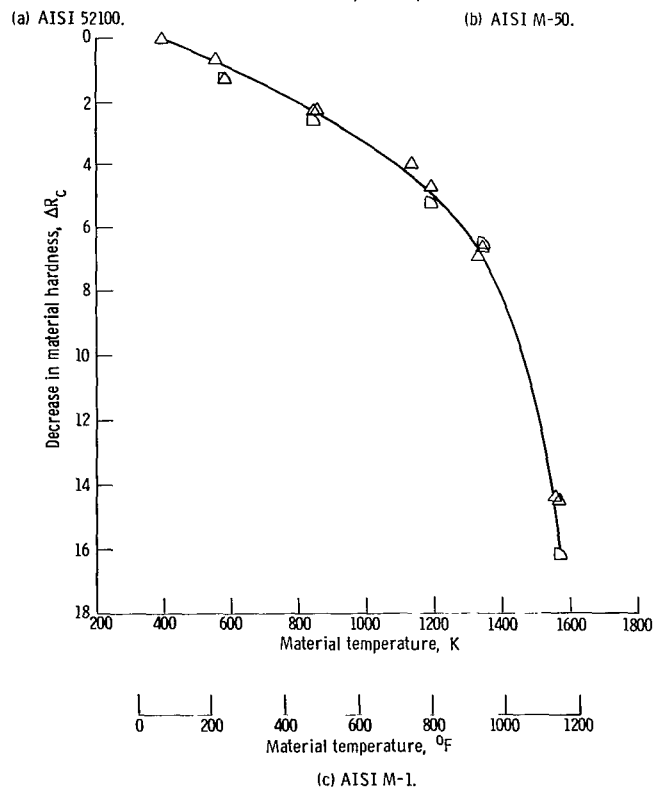
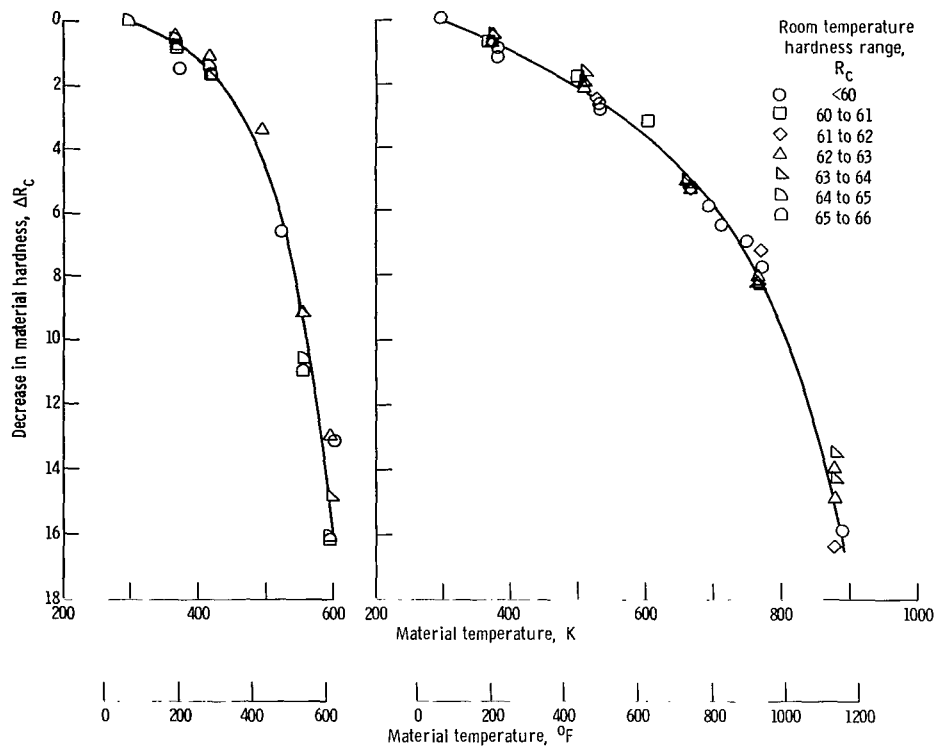
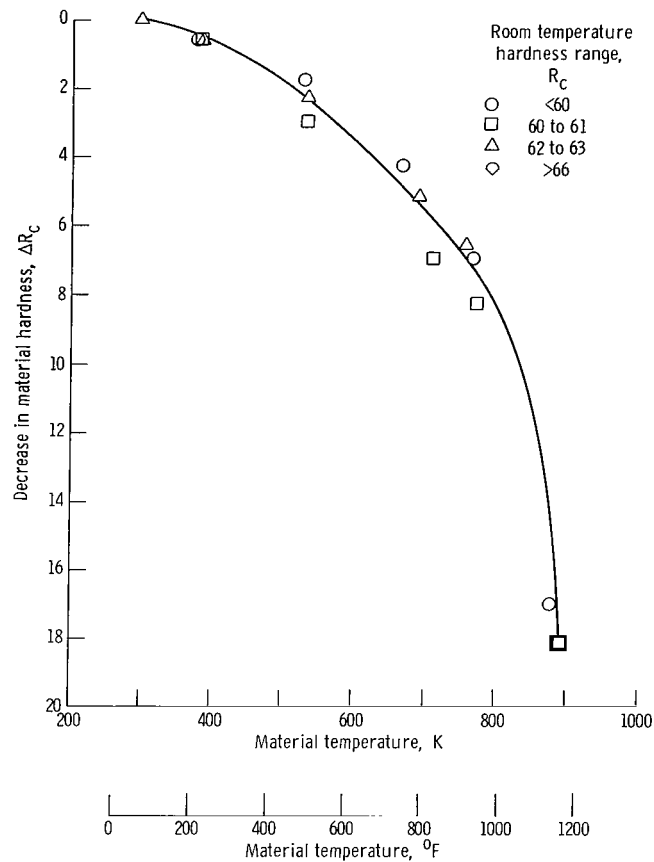
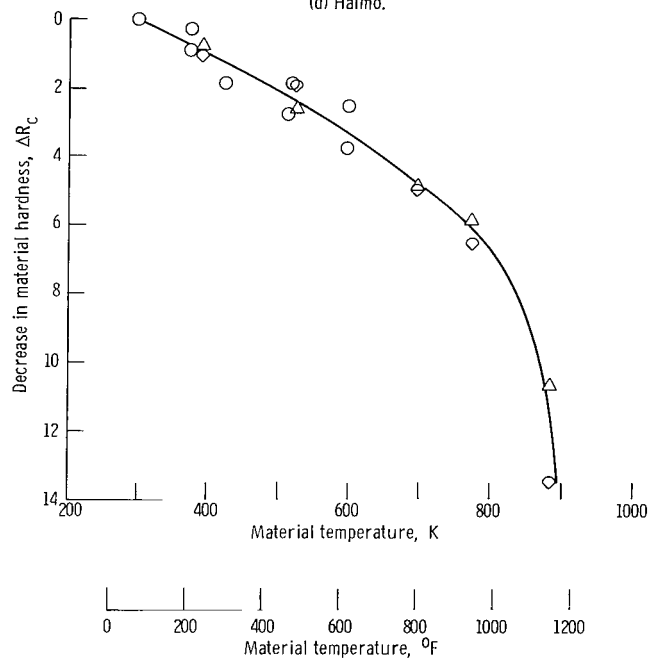


Figure 4. - Normalized short-term hardness data for five bearing steels.

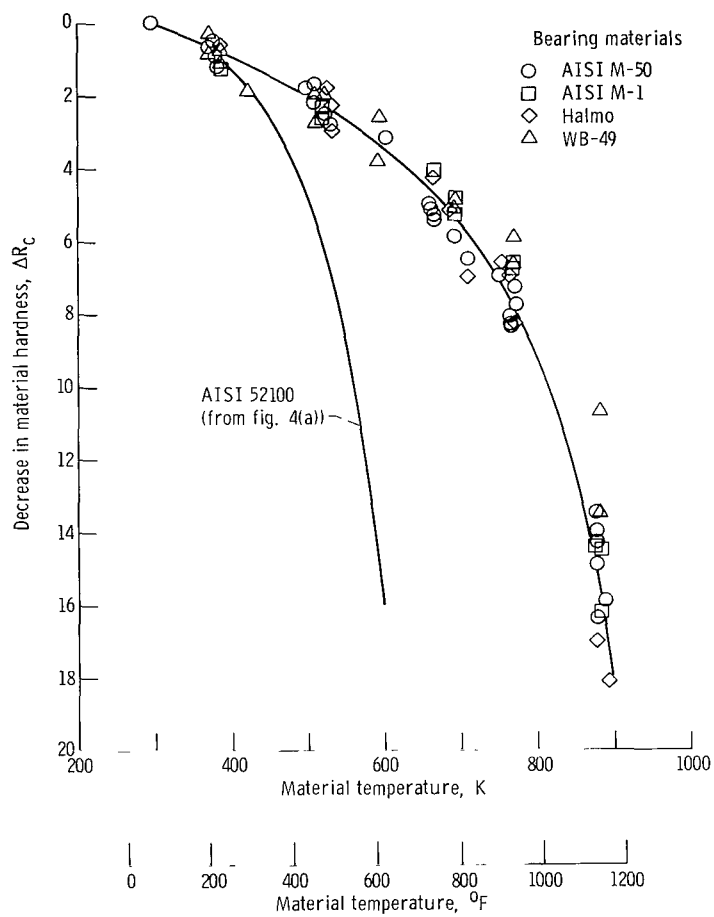


(d) Halmo.



(e) WB-49.

Figure 4. - Concluded.



(a) Cartesian coordinates.

Figure 5. - Combined normalized short-term hardness data for five bearing steels.

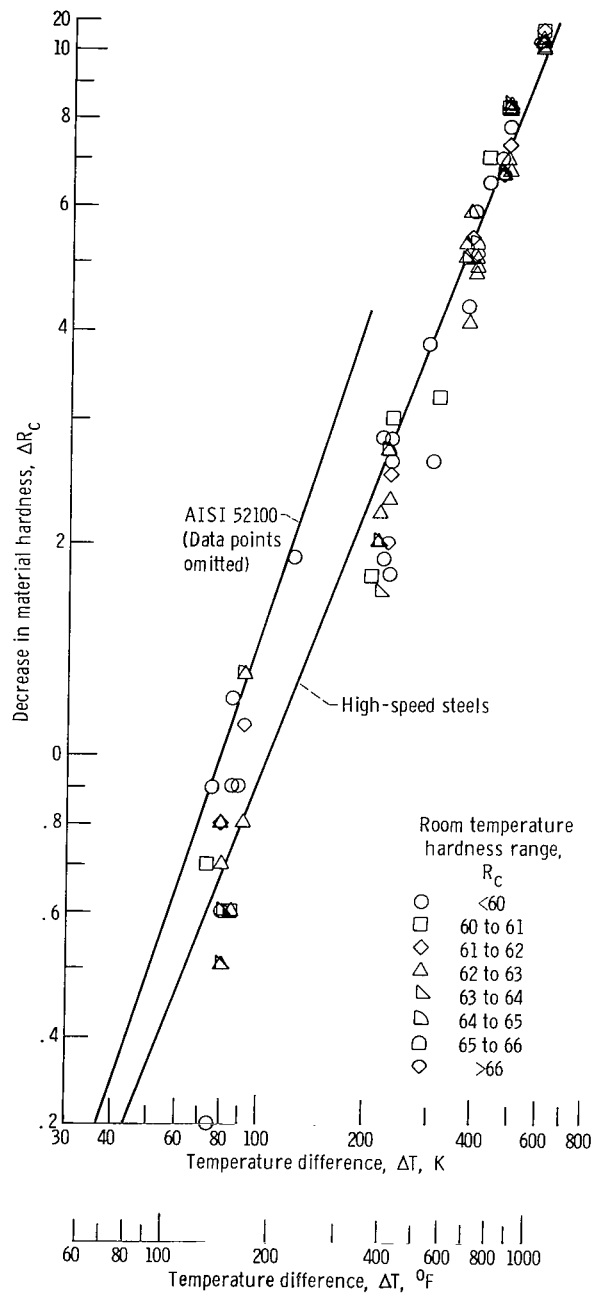
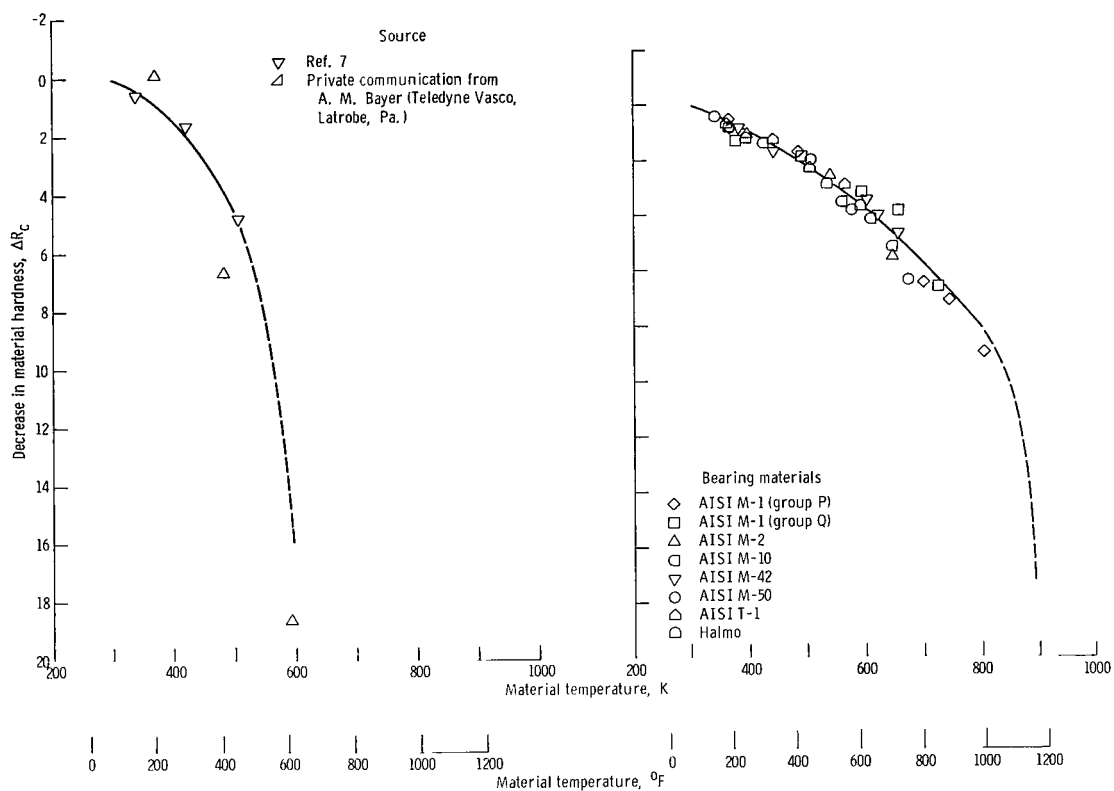
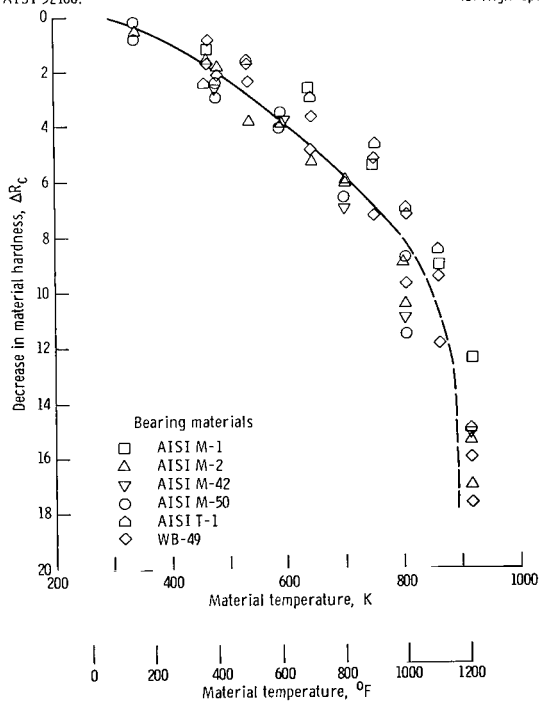


Figure 5. - Concluded.



(a) AISI 52100. (b) High-speed steels. (Data from ref. 7.)



(c) High-speed steels. (Data obtained in private communication from A. M. Bayer, Teledyne Vasco, Latrobe, Pa.)

Figure 6. - Comparison between theoretical and short-term hardness measurements.



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— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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